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Experimental investigations of effects of geometric curvature on the performance of a line focus concentrating collectors

[1*]Fatigun A. T., [1]Faweya E. B., [1]Aduloju K. A. and [2]Falaiye O. A.

[1]Energy Research Group, Department of Physics, Ekiti State University, Ado-Ekiti, Nigeria
[2]Department of Physics University of Ilorin, Ilorin, Nigeria

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ABSTRACT

This research work presents experimental investigation of the effect of geometric curvature on the performance of a stationary line focus solar collector. A three segments prototype line focus concentrating structures was constructed with each segment having geometric curvatures namely; Hyperbola, Sub-cylindrical and Parabola. The experimental investigation was carried out in South western part of Nigria (Ado-Ekiti) between 10th and 16. th of July 2012 during which the weather condition was characterized with frequent cloud cover, rain and drizzling. Based on the daily average value, The maximum value of absorber output temperature recorded during the 7 days of experimental setup was 116^{0}C .However, the sub-cylindrical geometric curvature segment was found to be the most efficient compared to the hyperbolic and parabolic geometric curvatures -with a difference of up to 10^{0}C on a clear day. The Concentration ratio of the prototype system was estimated to be 2.86, daily average value of the useful heat gain rate was estimated to be 9.6W while the heat loss coefficient is approximately 4.637W/m^2-K. The highest Instantaneous performance efficiency (based on beam radiation (I_b) alone) observed for a clear day was approximately 45%. These observations showed that the effect of geometric curvature is significant on the performance efficiency.

Keywords: Geometric curvature, Concentration Ratio, Absorber Temperature, Ambient Temperature, Heat loss coefficient.

INTRODUCTION

Energy is considered a prime agent in the generation of wealth and a significant factor in world economic development. One of the most widely accepted definitions of sustainable development is: ‘’development that meets the needs of the present without compromising the ability of future generation to meet their own need ‘’ [1]. Therefore, for a sustainable development within a society, it is required that a sustainable supply of energy and effective and efficient utilization of energy resources are secured without causing environmental or health problem. This is why there is a close connection between renewable energy sources like (solar energy, wind energy, geothermal energy) and sustainable development. At the end of 2001 the total installed capacity of renewable energy system was equivalent to 9% of the total electricity generation [2]. This percentage is far too low for development to be sustainable considering the importance of renewable energy. By applying intensive scenario the global consumption of renewable energy sources by 2050 would reach 318exajoules [3]. Because of the desirable environmental, safety consideration and its relative abundance it is widely believed that solar energy should be utilized instead of other alternative energy forms, even when the costs involved are slightly higher [1]. In this paper we consider solar thermal systems as an effective means of harnessing solar radiation energy. The prime agent in any solar thermal system is the solar energy collector. Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The amount of energy collected and converted to heat energy depends on numbers of factors which includes the location where it is installed in term of the latitude and longitude, design and structural consideration, types of material used e.t.c. The major component of any solar thermal system is the solar collector. This device can either absorbs the incoming solar radiation energy directly without concentration or absorb concentrated solar radiation energy at its point of focus. The absorbed heat energy can be used directly or transfer to heat storage medium. There are basically two types of solar collectors: non-concentrating and concentrating collector. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux [4]. In this study, we investigate the effect of geometric curvature on the performance efficiency of line focus solar concentrators in stationary mode. We also carry out performance analysis on our prototype solar collector base on the experimental measurement.

MATERIALS AND METHODS

2.1 Design and Construction

The prototyped line focus solar collector was constructed using flexible plywood, wooden planks, silver coated acrylic mirror, copper tube (painted black), used fluorescent tube and top bond glue. Three different geometrical curvatures namely: hyperbolic, sub-cylindrical and parabolic were plot and cut out on piece of cardboard which serve as the templates. These templates were then marked out on a 1 inch thick wooden frame measuring 3ft by 1 ft. The curvatures were carefully cut out side by side on the wooden frame to produce three segments of different geometric curvature on a single frame. Two of such frames were produced to serve as the top and bottom frame. Flexible plywood was bent over each segment and nailed, thereby producing three segments structure with different geometric curvatures. Acrylic silver coated mirror was pasted on each segments using top bond glue. These produces concave reflective surfaces with different position of focus depending on the geometric curvature. The position of focus for the hyperbolic segment was located inside the curvature while that of sub-cylindrical and parabolic curvature were located on the surface and above the surface respectively. Copper tube painted dull black with concentric glass cover around it was placed along the focal line of each curvature. Used fluorescent tube serve as the concentric glass cover after removing the metal terminals and this was insulated on both sides using local cotton wool. The complete structure of our three segment prototype line focus solar collector is as shown in figure 1 below.

Fig. 1: Prototype line focus concentrating collector

2.2 Experimental Setup / Test procedure

The experimental setup is as shown in figure 1 above. The collector is oriented in the east – west direction and horizontal. It is inclined slightly towards south and is in stationary mode. Input temperature, output temperature, glass cover temperature, ambient temperature and relative humidity were measured from 9:00 hour till 17:00 hour of the day at 30 minutes intervals.

2.3 Design Specification, Operational and Meteorological Parameters

The performance analysis of the prototype sub-cylindrical parabolic concentrating collector was carried out based on the following design specifications, operational and meteorological

Table 1 : operational and meteorological parameters

Date	10th to 15th July 2012.
Duration	9:00 to 17:00 hour.
Absorber tube inner diameter (D_i)	0.014m
Absorber tube outer diameter (D_o)	0.015m
Glass cover inner diameter (D_{ci})	0.0296m
Glass cover outer diameter (D_{co})	0.03m
Mean temperature of Absorber tube (T_{pm})	337.4K
Mean Temperature of the Glass cover (T_c)	341.5K
Ambient Temperature (T_a)	305.23K
Average wind speed (v)	3.33m/s
Latitude (ϕ)	7.71^0N
Emissivity of absorber tube surface (ε_p)	0.15
Emissivity of glass cover (ε_c)	0.88
Specular reflectivity of concentrator surface (ρ)	0.85
Glass cover transmissivity for solar radiation (τ)	0.90
Absorber tube emissivity/absorptivity product for beam radiation $(\tau\alpha)_b$	0.95
Glass cover emissivity/absorptivity product for beam radiation $(\tau\alpha)_b$	0.95
Intercept factor γ	0.90
Average value of solar beam radiation I_b	$150W^2/m^2$

3.0 Calculation of Solar Radiation Geometry

Solar radiation geometry for the location of the experimental setup (Ado-Ekiti) was determined. Those parameters estimated include the Solar Declination Angle δ, Tilt Factor r_b, Zenith Angle θ_z, Day Length N_d and the angle of incidence θ. The estimated parameters can be related by a general equation to ϕ the latitude, β the slope, γ the surface azimuth angle, ω the hour angle using semi-empirical equation.

Cooper [5] has given the following simple relation for calculating the declination

$$\delta(in\ degree) = 23.45 \sin\left\{\frac{360}{365}\right\}(284 + n) \qquad \text{……………………………1}$$

where n is the day of the year.

For a given geographical location, in the absence of the earth's refractive atmosphere, the trigonometry relation between the sun (the center of solar disk) and a horizontal surface has been determined accurately. It has been shown that for horizontal surface ($\beta=0^0$), the zenith angle can be obtained from the relation

$$\cos\theta z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega \qquad \text{……………………………… 2}$$

While the angle of incidence can be calculated from the relation

$$\cos\theta = \sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta) \qquad \text{…………………………….. 3}$$

For a horizontal surface, the hour angle corresponding to sunrise or sunset (ω) can be obtained from equation 2 by substituting the value of 90^0 for the zenith angle. We obtained

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$$\omega = cos^{-1}(-tan\phi \tan\delta) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Equation 4 yields a positive and a negative value for ω, the positive corresponding to sunrise and the negative to sunset. Since 15^0 of the hour angle is equivalent to 1 hour, the corresponding day length (in hours) is obtained as

$$N_d = \frac{2}{15} cos^{-1}(-tan\phi \tan\delta) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

The tilt factor r_b for instantaneous hourly beam radiation is the ratio of cosine of angle of incidence to the cosine of zenith angle.

$$r_b = \frac{\cos\theta}{\cos\theta z} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

3.1 Performance evaluation/analysis

For the purpose of analysis, it is assume that the solar radiation flux falling on the collector is uniform throughout the entire length. It is also assume that the temperature drops across the absorber tube and the glass cover are negligible.

The concentration ratio of the collector is given by

$$C = \frac{Effective\ aperture\ area}{Absorber\ tube\ area} = \frac{(W - D_o)}{\pi D_o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

where ; W is the collector aperture.

An energy balance on an elementary slice dx of the absorber tube, at a distance x from the inlet, yields the following equation for a steady state:

$$dq_u = [I_b r_b (W - D_o)\rho\gamma(\tau\alpha)_b + I_b r_b (\tau\alpha)_b - U_l \pi D_o (T_p - T_a)]dx \qquad \ldots\ldots\ldots\ldots..8$$

Where ;

dq_u = useful heat gain rate for a length dx

ρ = specular reflectivity of the concentrator surface

γ = intercept factor

$(\tau\alpha)_b$ = average transmissivity-absorptivity product for beam radiation

U_l = overall heat loss coefficient

Mullick and Nanda [6] developed a semi-empirical equation for directly calculating the overall heat loss coefficient U_l of equation 8. Their equation eliminates the need for an iterative calculation and is given as.

$$\frac{1}{U_l} = \frac{1}{C_3 (T_{pm} - T_c)^{0.25} + \left[\frac{\sigma(T_{pm}^2 + T_c^2)(T_{pm} + T_c)}{\left\{\frac{1}{\varepsilon_p} + \frac{D_o}{D_{ci}}\left(\frac{1}{\varepsilon_c} - 1\right)\right\}}\right] + \left(\frac{D_o}{D_{co}}\right)\left(\frac{1}{h_w + \sigma\varepsilon_c(T_c^2 + T_a^2)(T_c + T_a)}\right)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 9$$

The constant C_3 was obtained from the correlation of Raithby and Hollands [7] and is given by the expression;

$$C_3 = \frac{17.74}{(T_{pm} + T_c)^{0.4} D_o (D_o^{-0.75} + D_{ci}^{-0.75})}$$

The wind heat transfer coefficient (h_w of equation 9) on the outside surface of the glass cover can be calculated using correlation based on the data of Hilpert as used by Sukhatme and Nayak [4]. The data can be correlated by the equation

$$N_u = C_1 Re^n \quad \text{...10}$$

where C_1 and n are constant having the following values;

For 40 < Re < 4000, C_1=0.615, n = 0.466
For 4000 < Re < 40,000 C_1 = 0.174, n = 0.618
For 40,000 < Re < 400,000, C_1 = 0.0239, n=0.805

Churchill and Berstein [8] also made a comprehensive analysis of the data available for cross flow across a cylinder and developed the following correlation for estimating the Nusselt number N_u

$$N_u = 0.3 + \frac{0.62\, Re^{1/2} Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}}\left[1 + \left(\frac{Re}{282000}\right)^{\frac{5}{4}}\right]^{4/5} \quad \text{................................11}$$

Equation 11 is valid for all values of Re up to 10^7

The instantaneous collection efficiency η_i can be determined based on the beam radiation only using the relation

$$\eta_i = \frac{q_u}{I_b r_b WL} \quad \text{..12}$$

Performance of the prototype line focus concentrator was analyzed using equations 1 to 12 and the result obtained is presented in the next section.

RESULTS AND DISCUSSION

Meteorological parameter estimated for Ado-Ekiti (latitude 7.71^0 N, longitudes 5.25^0 E) for the purpose of our analysis includes the followings: Declination Angle δ, Tilt Factor r_b, Zenith Angle θ_z, Day Length N_d and the angle of incidence θ. Declination angle was estimated to be 22.04^0 while the sunrise/sunset hour angle was calculated to be 93.14^0. Daylength calculated for Ado-Ekiti on 11th July 2012 was 12hours 28 min which agree with the forecast of 12hour: 33min by weather 2 forecast. Approximately 3hours Sunshine duration was forecasted within the 12hours 33min daylength due to frequent cloud cover while the daily value of relative humidity measured was about 78% on the average. Figure 2 showed the hourly variation of collector tilt factor. Tilt factor decreases gradually with the time of the day getting to minimum value of 1.0329 by noon when the sun is expected to be at the zenith and then increases gradually afterward. Observation showed that the performance of a stationary line focus collector improve with decreasing value of tilt factor and the absorber output temperature is maximum at this hour on most days. This observation implies that the tilt factor is a function of the direction of beam radiation with respect to the collector aperture and therefore intermittent tracking will be required for better performance. Figure 3 to 9 show the hourly variation of the ambient temperature and output temperatures of the three segments of the prototype line focus collector for different days of experimental set-up. Observation show that the absorber output temperature increases gradually with time of the day and reaching its maximum value around noon on a clear day. The optimum operating hour was observed to be between 10:00 and 15:00 hours for each day. The absorber temperature was persistently higher than the ambient temperature with daily average difference of about 29^0C on some days. Concentration ratio of the system was calculated to be 2.86 though minimum of 10 was recommended for high temperature output. The maximum value of absorber output temperature recorded during the 7 days of experimental setup was 116^0C but higher value is possible depending on the concentration ratio. Useful heat gain rate was estimated to be 9.6W while the heat loss coefficient was 4.637W/m^2-K. Instantaneous performance efficiency based on beam radiation alone for 11th July was estimated to be approximately 45%. Study showed that the effect of geometric curvature is significant on the performance efficiency. The performance of sub-spherical structure is slightly better when compared to the hyperbolic and parabolic structure with daily average temperature difference of up to 10^0C on a clear day.

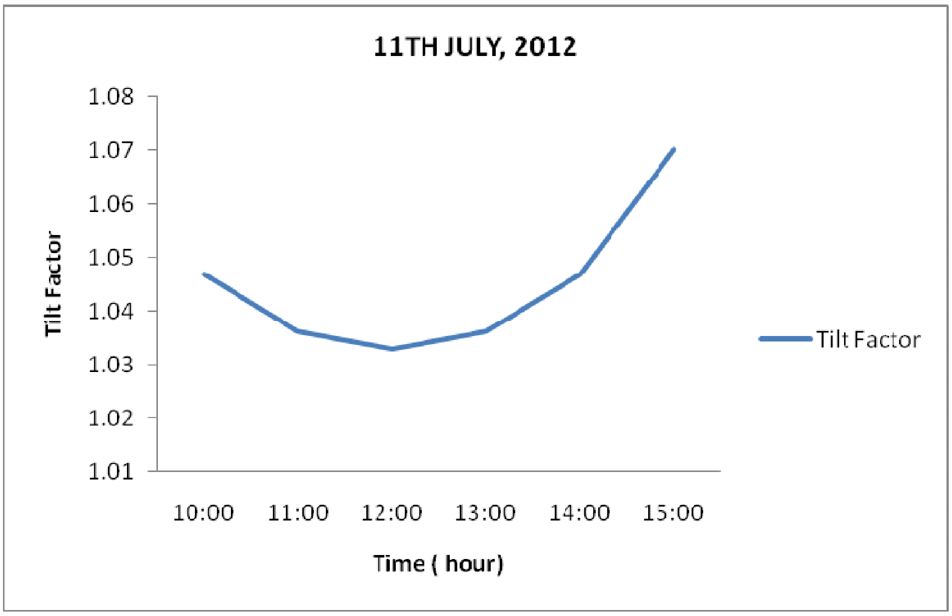

Fig. 2: Hourly variation of collector tilt factor

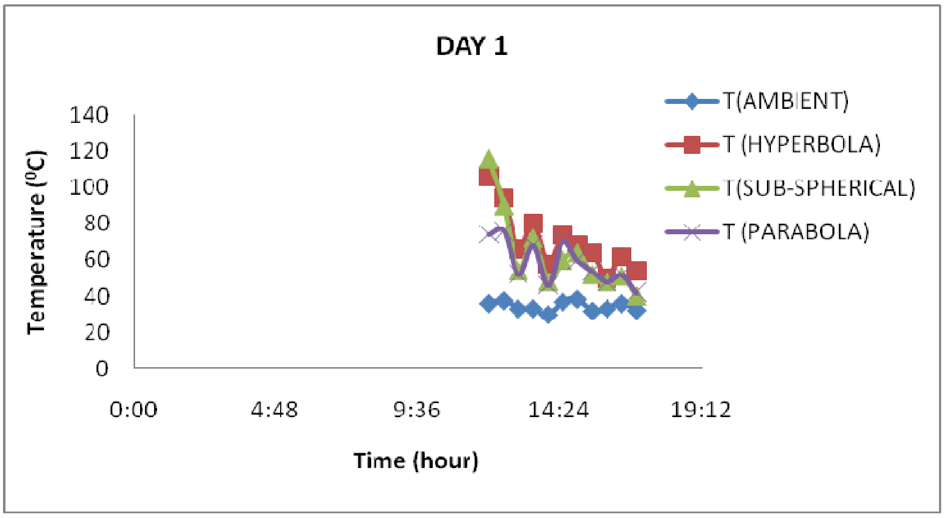

Fig. 3: Variation of ambient and output temperatures with time of the day

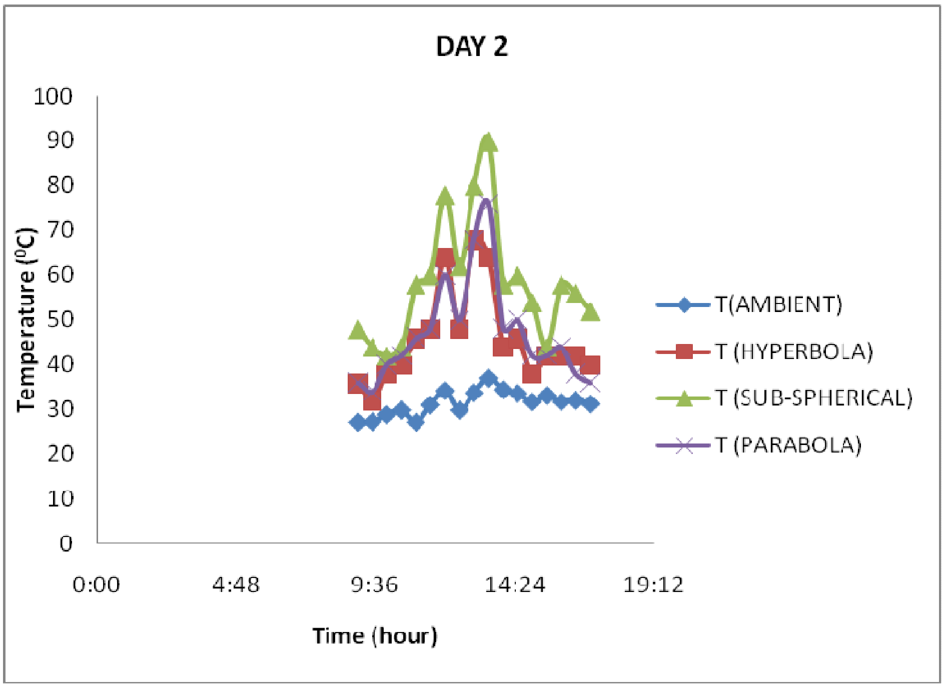

Fig. 4: Variation of ambient and output temperatures with time of the day

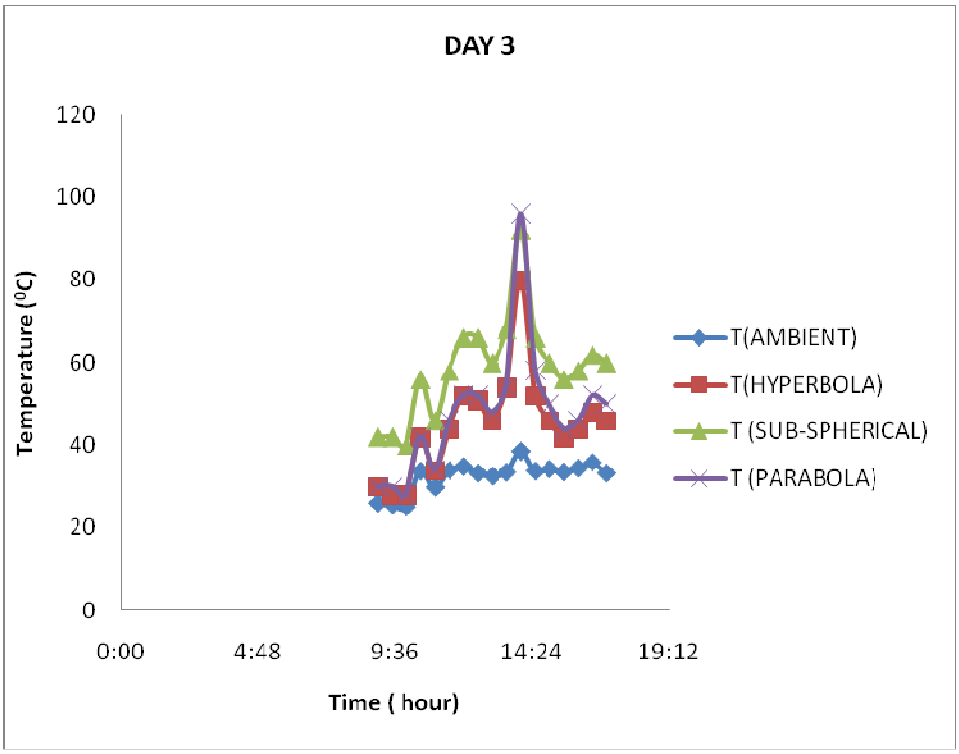

Fig. 5: Variation of ambient and output temperatures with time of the day

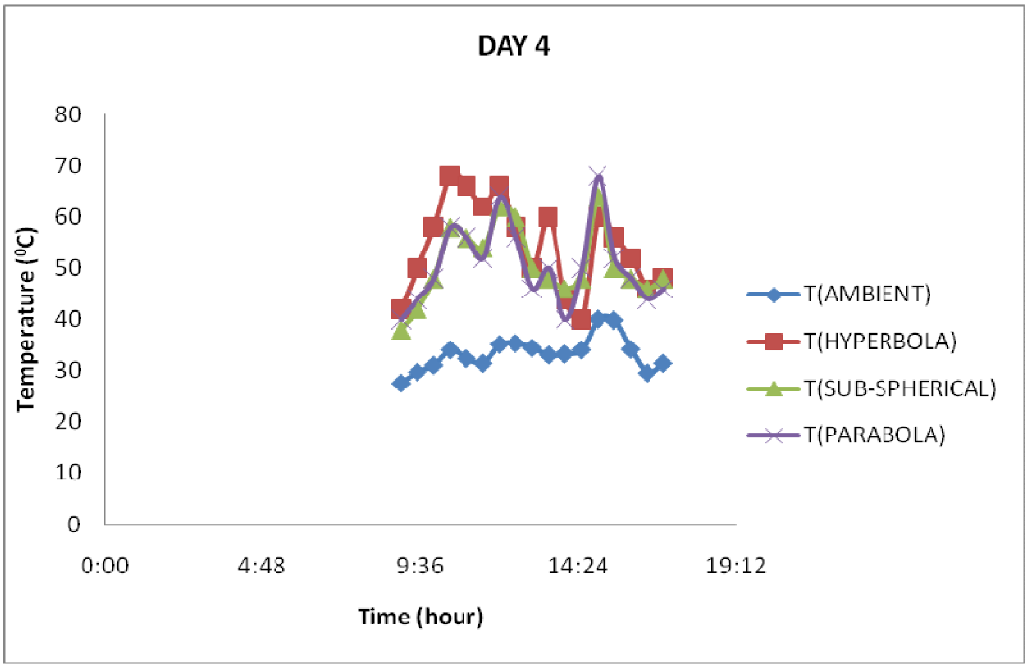

Fig. 6: Variation of ambient and output temperatures with time of the day

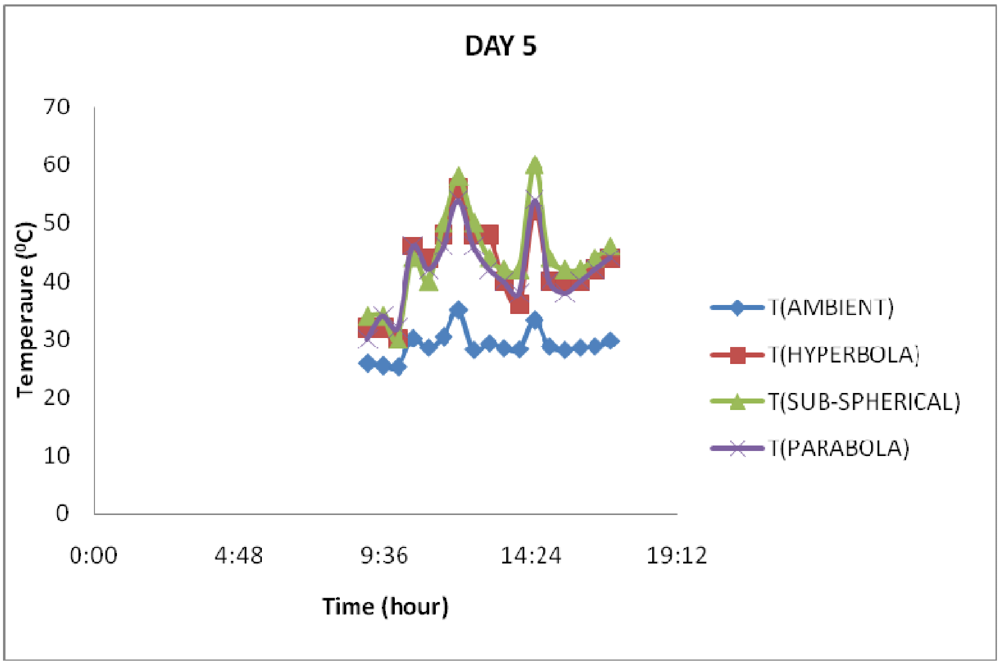

Fig. 7: Variation of ambient and output temperatures with time of the day

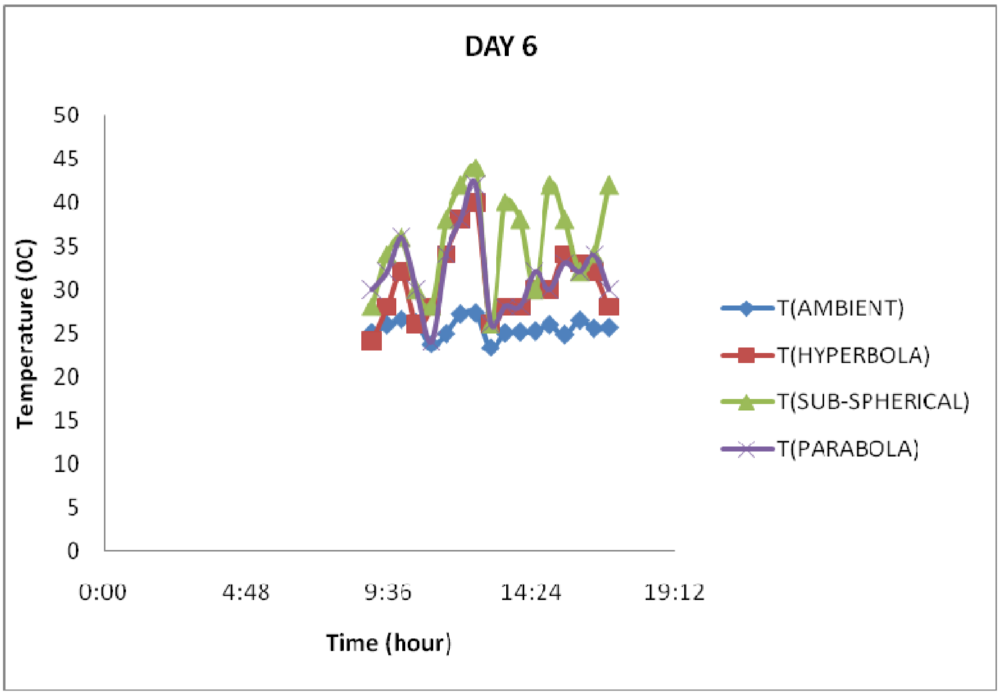

Fig. 8: Variation of ambient and output temperatures with time of the day

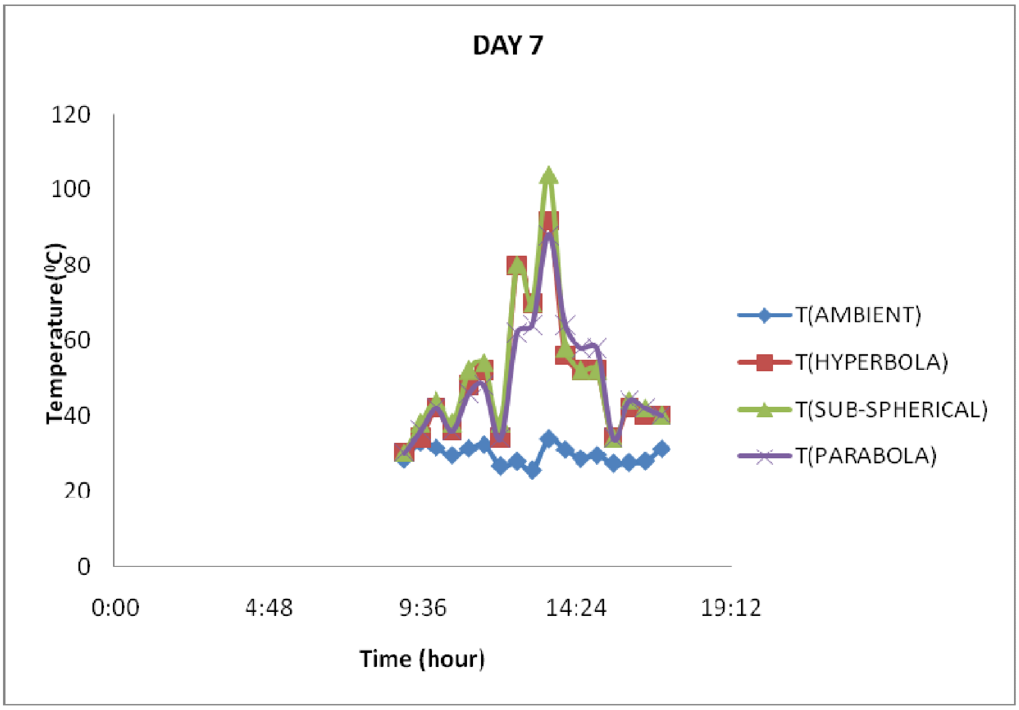

Fig. 9: Variation of ambient and output temperatures with time of the day.

CONCLUSION

Experimental investigation was carried out on a three segment line focus concentrating collector in stationary mode. Each of the segments traced out a hyperbolic, sub-cylindrical and parabolic geometric curvature respectively. Study show that the effect of structural geometry is significant on the performance efficiency of a line focus collector. The useful heat gain rate of the system was estimated to be 9.6W while the heat loss coefficient was 4.637W/m^2-K. Instantaneous performance efficiency based on beam radiation alone for 11th July was estimated to be approximately 45%.

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